

## INTERFEROMETRIC EVIDENCE FOR RESOLVED WARM DUST IN THE DQ TAU SYSTEM

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### ABSTRACT

We report on near-infrared (IR) interferometric observations of the double-lined pre-main sequence binary system DQ Tau. We model these data with a visual orbit for DQ Tau supported by the spectroscopic orbit and analysis of Mathieu et al. Further, DQ Tau exhibits significant near-IR excess; modeling our data requires inclusion of near-IR light from an “excess” source. Remarkably, the excess source is resolved in our data, similar in scale to the binary itself ( $\sim 0.2$  AU at apastron), rather than the larger circumbinary disk ( $\sim 0.4$  AU radius). Our observations support the Mathieu et al. and Carr et al. inference of significant warm material near the DQ Tau binary.

*Key words:* binaries: spectroscopic – circumstellar matter – stars: individual (DQ Tau) – stars: pre-main sequence

### 1. INTRODUCTION

DQ Tau (HBC 72) is among a small number of known “classical” T-Tauri (CTTS) spectroscopic binaries. DQ Tau’s strong H $\alpha$  emission and de facto T Tauri status was reported by Joy (1949). The system has a spectral energy distribution (SED) typical of CTTS, with strong near- and mid-infrared (IR) excess (Strom et al. 1989; Skrutskie et al. 1990; Mathieu et al. 1997, Section 2). H $\alpha$  emission and continuum veiling indicate significant accretion onto the stars (Valenti et al. 1993; Hartigan et al. 1995; Basri et al. 1997). Mathieu et al. (1997, herein M1997) established DQ Tau as an eccentric, short-period (15.8 d), double-lined spectroscopic binary composed of similar late K-stars; presumably the mid-IR excess is due to emission from a circumbinary disk. Further, M1997 and Basri et al. (1997, herein B1997) identified photometric and spectroscopic variability at the orbit period and phased near periastron, interpreting these variations as enhanced accretion as the stellar components encounter streams of infalling material from the circumbinary disk. Recently Salter et al. (2008) reported a mm flare in DQ Tau, but interpret the flare as interacting stellar magnetospheres similar to that seen in V773 Tau A (Massi et al. 2008).

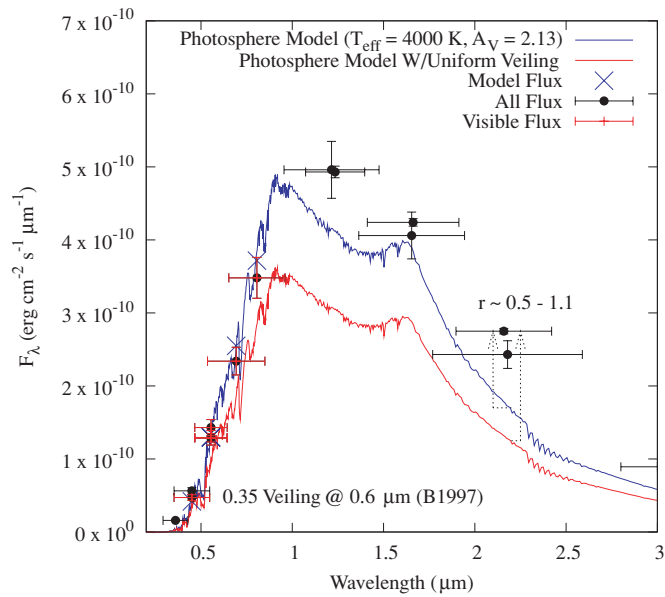
Binary systems are expected to clear inner gaps in their circumbinary disks (out to several times the binary semimajor axis) as material is dynamically ejected by the components (Artymowicz & Lubow 1994; Pichardo et al. 2005). Jensen & Mathieu (1997) report SED evidence for such inner-disk clearings in a set of T Tauri binaries. The SEDs in these systems show a deficit of near-IR emission relative to mid-IR flux—interpreted as a lack of the warmer inner-disk material that has been dispersed by the stars’ orbital motion. Conversely, the DQ Tau SED (and a few others, e.g., AK Sco (Jensen & Mathieu 1997), and UZ Tau (E Jensen et al. 2007)) exhibits no such near-IR deficit, leading M1997 to conclude “there is clearly warm material within the binary orbit.” M1997 modeled the DQ Tau SED with a modest ( $5 \times 10^{-10} M_{\odot}$ ) amount of warm (1000 K), optically thin material in the DQ Tau binary region. Carr et al. (2001, herein C2001) supported this conclusion with IR spectroscopic detection of warm (1200 K) CO gas emission from DQ Tau.

The presence of material inside the expected DQ Tau dynamical gap is unsurprising: the system shows strong accretion diagnostics. But the amount and morphology of this “inner” material bears on how such pre-main sequence (PMS), binary systems interact with and accrete material from their circumbinary reservoir, and motivates study with the highest resolution techniques available. Here we report on observations of DQ Tau with the Keck Interferometer (KI; Colavita et al. 2003). These observations partially resolve the DQ Tau system, and allow us to model the system visual orbit based on the spectroscopic orbit by M1997. Further, we find that we must account for a static “excess” flux which is compact, but partially resolved in these data. We interpret this excess source with possible morphological models for the warm material postulated by M1997 and C2001, and discuss implications on inner material and accretion in the DQ Tau system.

### 2. DQ TAU SPECTRAL ENERGY DISTRIBUTION

The DQ Tau SED has been studied by Strom et al. (1989), Skrutskie et al. (1990); Hartigan et al. (1995), and M1997; as it bears on our KI data analysis we summarize the SED here. Figure 1 shows a visible and near-IR SED model for the DQ Tau stellar photospheres derived using photometry from Strom et al. (1989) and Two Micron All Sky Survey (Skrutskie et al. 2006). Adopting published extinction estimates ( $A_V = 2.13$ ; Strom et al. 1989) and photospheric parameters ( $T_{\text{eff}} = 4000$  K,  $\log g = 4.0$ , solar abundance; M1997), we can model photometry between 0.45 and 1  $\mu\text{m}$  (excluding blue accretion flux and IR excess) with a single photosphere (the stellar components of DQ Tau are nearly identical; M1997). We find the net photosphere model shown in Figure 1, corresponding to a total stellar luminosity of  $0.88 L_{\odot}$  for  $D = 140$  pc, in good agreement with previous estimates (e.g., Strom et al. 1989; M1997). However, these estimates ignore the significant ( $0.35 \pm 0.15$  at 0.6  $\mu\text{m}$ ) veiling reported by B1997. An alternative model assuming uniform veiling between 0.45 and 1  $\mu\text{m}$  is also given in Figure 1, corresponding to total stellar luminosity of  $0.65 L_{\odot}$ . The total luminosity of the DQ Tau photospheres is likely between these two extremes.

DQ Tau’s SED exhibits strong IR excess beyond 1  $\mu\text{m}$ . M1997 modeled this excess with a power law, and particularly



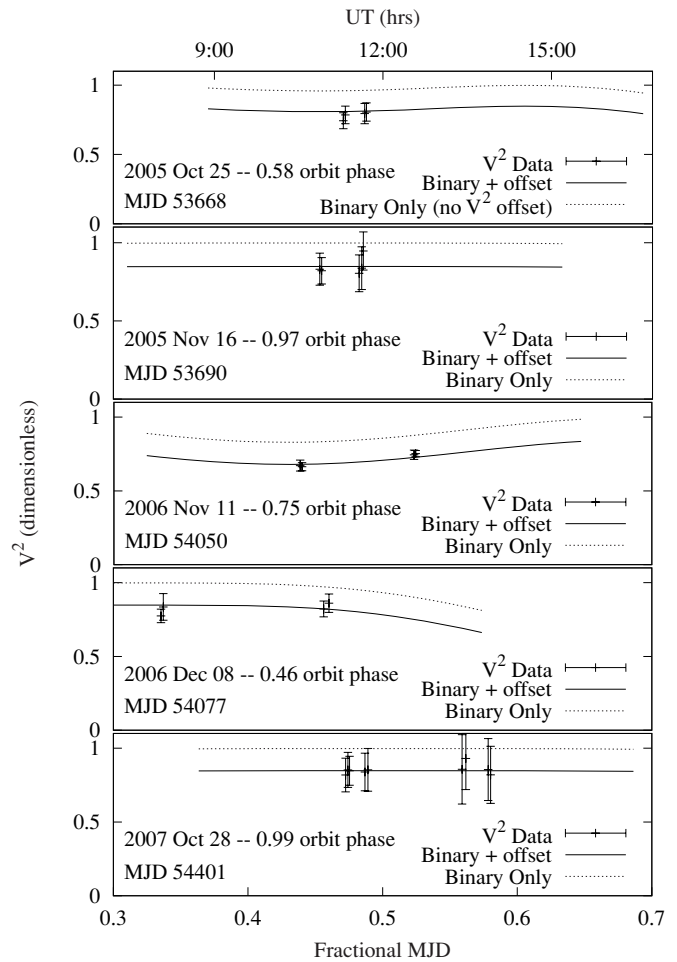
**Figure 1.** DQ Tau SED model. We model the DQ Tau photospheres with a 4000 K template (M1997) and significant extinction ( $A_V = 2.13$ ; Strom et al. 1989). The red curve shows an alternative photospheric model assuming a veiling fraction of  $0.35 \pm 0.15$  (B1997). The fractional  $K$ -excess over the photosphere ( $r$ ) ranges between 0.5 and 1.1 depending on which photosphere model is adopted.

argued for the presence of a cooler circumbinary disk and additional warm material within the binary orbit based on substantial excess over the stellar emission between 1 and  $5 \mu\text{m}$ . Most significant for our purposes is the excess in  $K$ -band ( $2.2 \mu\text{m}$ )—highlighted in Figure 1. Based on the photospheric models from above we estimate the fractional excess  $r$  at  $K$  over the stellar contribution to be in the range of 0.5–1.1 (modulo intrinsic  $K$ -variability of the system; we return to this question in Section 4). The bottom of this range agrees with similar estimates from Strom et al. (1989) and Skrutskie et al. (1990), while higher values result from incorporating the veiling estimate of B1997. This SED model makes it clear our KI observations will contain flux from both the DQ Tau binary components and additional material, but the exact value of the excess  $K$ -emission over stellar is uncertain to a factor of 2.

### 3. OBSERVATIONS AND ORBITAL MODELING

**KI observations.** The KI observable used for these measurements is the fringe contrast or *visibility* (specifically, power-normalized visibility modulus squared,  $V^2$ ) of an observed brightness distribution on the sky. KI observed DQ Tau in  $K$  band on five nights between 2005 October 25 and 2007 October 28, a data set spanning roughly two years and 49 orbital periods. DQ Tau and calibration objects were typically observed multiple times during each of these nights, and each observation (scan) was approximately 130 sec long. As in previous publications, our KI  $V^2$  calibration follows standard procedures described in Colavita et al. (2003). For this analysis we use HD 27282 (G8 V) as our calibration object, resulting in 26 calibrated visibility scans on DQ Tau over five epochs. The  $V^2$  observations are depicted in Figure 2, along with our best-fit orbit model (discussed below). Orbital analysis methods for such  $V^2$  observations are discussed in Boden et al. (2000) and not repeated here.

Figure 2 shows the DQ Tau calibrated visibilities are significantly less than one in all five epochs—indicating resolved

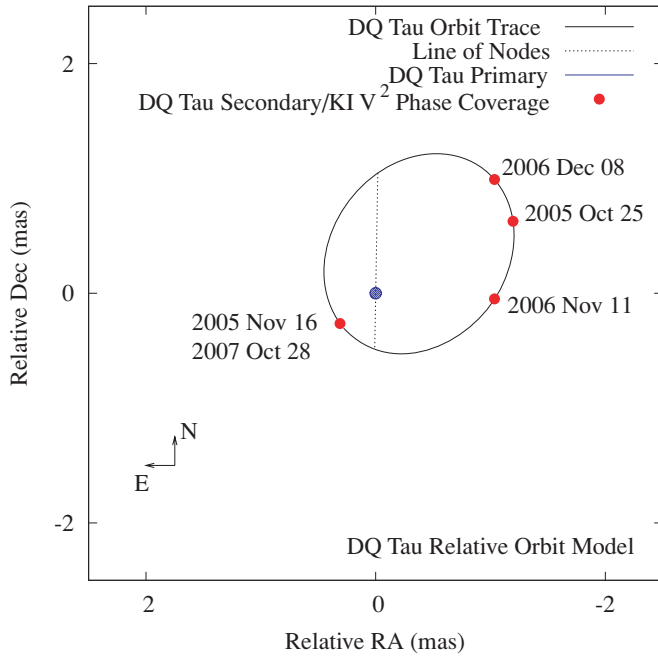


**Figure 2.** KI data/model comparisons for DQ Tau  $V^2$  observations. Here, we give comparisons for our five epochs of KI  $V^2$  observations and our best-fit orbital model with and without the estimated visibility offset. In each frame both KI data and model are shown.

structure in our observations. Further, the five epochs show variability with time and hour angle—indicating the source appearance changes with time (e.g., with phase of the DQ Tau binary orbit), and is nonaxisymmetric (both as expected for a resolved binary system).

**Orbit model.** As in previous analyses (e.g., Boden et al. 2000, 2005, 2007) we model the KI visibilities with a binary source. The DQ Tau physical parameters from M1997 and putative 140 pc distance imply an apparent semi-major axis on the order of 1 mas. This apparent separation is marginally resolved in our data (projected fringe spacing of 5.1 mas), and does not allow an independent solution for the binary visual orbit. Therefore we have constrained our orbital modeling with parameters from M1997 (with period slightly revised by Huerta et al. 2005). Effectively we solve only for  $\Omega$  and the sense of rotation on the sky (i.e., whether  $i$  is greater or less than  $90^\circ$ ). Further, from Section 2 it is necessary to account for the visibility contribution of DQ Tau’s  $K$ -excess (even if that flux is incoherent on angular scales measured in these data). We find it sufficient to model the visibility due to the excess flux with a single, static visibility offset parameter  $V_{\text{offset}}^2$  (discussed in Section 4).

Figure 3 depicts our relative visual orbit model, with the primary rendered at the origin, and the secondary rendered at the five orbit phases of our KI data. Figure 2 shows the comparison of the KI data and predictions; the model clearly matches the



**Figure 3.** Relative visual orbit of DQ Tau. The relative visual orbit of the DQ Tau system is given, with the primary rendered at the origin, and the secondary position shown at the five epochs/orbit phases of our observations (two of our epochs are at periastron).

data well within the estimated errors. Table 1 summarizes our DQ Tau orbit model as adopted from M1997 and derived here. Our data show that the orbit motion is clockwise on the sky (retrograde); we adopt an inclination value ( $157^\circ$ ) constrained by the M1997  $\sin i$  estimate and reflecting retrograde orbit motion.

#### 4. INTERPRETING THE VISIBILITY OFFSET

$V_{\text{offset}}^2$  accounts for contributions from DQ Tau's  $K$ -excess in our modeling. We have taken this visibility offset as static, that is invariant in time and with baseline projection angle; this construct warrants some consideration. First, we note that M1997 and B1997 reported photometric variability in DQ Tau, but this was strongest in blue ( $U$  &  $B$ ) colors and attributed to variability in accretion luminosity; as we will argue below, spectrophotometric monitoring suggests changes in the system  $K$  flux are modest. Second, the assumption of an offset that is independent of baseline projection de facto assumes that the  $K$ -excess centroid is centered (coaxial) on the binary center of mass/light (for an equal-mass binary), and is itself axially symmetric. Artymowicz & Lubow (1996) have modeled accretion in systems such as DQ Tau, and their modeling clearly shows time-variable and nonaxisymmetric structures. These time-variable features call into question our static visibility offset construct, but the degree of visibility variability will depend on the relative intensity of symmetric and nonsymmetric components of the  $K$  flux in the DQ Tau excess, and the spatial frequency coverage in our interferometric data. In our last epoch (2007 October 28; Figure 2, bottom) we specifically made the observation at periastron, and pushed the KI instrument to its maximum range in hour angle (roughly four hours) to test this static offset/axisymmetric emission assumption to the greatest extent possible. Data from this last epoch show no significant signs of variation with hour angle, supporting the axisymmetric emission construct. Given these considerations we settle on a static visibility offset to account for the  $K$ -excess because

**Table 1**  
Orbital Parameters for DQ Tau

Orbital Parameter	M1997	This Work
Period (d)	15.8016	
$T_0$ (MJD)	49582.04	
$e$	0.556	
$K_{Aa}$ ( $\text{km s}^{-1}$ )	21.6	
$K_{Ab}$ ( $\text{km s}^{-1}$ )	22.4	
$\gamma$ ( $\text{km s}^{-1}$ )	22.4	
$\omega_A$ (deg)	228	
$\Omega$ (deg)		$179 \pm 10$
$i$ (deg)	23	157
$a$ (mas)		0.96
$\Delta K$ (mag)		0
$V_{\text{offset}}^2$		$0.15 \pm 0.03$

**Notes.** Our orbit model is constrained to parameters estimated by M1997 except for the period (Huerta et al. 2005),  $\Omega$  and  $V_{\text{offset}}^2$ . Note that the inclination  $i$  is constrained to the M1997 value, except that our data and modeling indicate that the motion of the binary is clockwise (retrograde) on the plane of the sky.

nothing more complicated is justified by our data: the binary plus static offset construct adequately model our KI data over their range of spatial frequency.

The (monochromatic)  $V^2$  of a two-component composite scene is given by:

$$V_{\text{composite}}^2 = \frac{V_1^2 + r^2 V_2^2 + 2r V_1 V_2 \cos \phi}{(1+r)^2} \rightarrow \frac{(V_1 + r V_2)^2}{(1+r)^2},$$

with  $V_1$  and  $V_2$  the visibilities of two components,  $r$  the flux ratio (2 to 1), and  $\phi$  the phase difference between the two fringes (e.g.,  $\phi = 2\pi/\lambda \mathbf{B} \cdot \mathbf{s}$  for a typical binary source); the second form assumes this phase offset is zero or the two sources are coaxial. Identifying  $V_1$  and  $V_2$  with the DQ Tau binary and the  $K$ -excess respectively, and evaluating the expression at a convenient binary phase (i.e., periastron, where  $V_{\text{binary}} \approx 1$ ) leaves:

$$V_{\text{composite}}^2(\text{periastron}) \approx \frac{(1 + r V_{\text{excess}})^2}{(1+r)^2} \approx 1 - V_{\text{offset}}^2.$$

This allows us to estimate the net visibility of the DQ Tau  $K$ -excess in terms of  $V_{\text{offset}}^2$  (Table 1) as:

$$V_{\text{excess}} = \frac{1}{r} \left( (1 - V_{\text{offset}}^2)^{(1/2)} (1+r) - 1 \right). \quad (1)$$

Evaluating Equation (1) with  $r$  in the range of 0.5–1.1 (Section 2) and  $V_{\text{offset}}^2 = 0.15$  (Table 1) yields  $V_{\text{excess}} = 0.77$ –0.85.

M1997 documents significant optical variability in DQ Tau, and attributes the variability to enhanced accretion near periastron. Pertinent to this discussion is the degree of  $K$  variability in the system. DQ Tau has been monitored with the CorMASS instrument (Wilson et al. 2001) as part of a T Tauri accretion variability program discussed in Bary et al. (2008). Analysis of these data suggests that  $K$  emission during enhanced accretion is approximately 20% brighter than during a quiescent phase. This variation is small compared to the factor of 2 uncertainty in  $r$  from the DQ Tau photospheric uncertainty.

Remarkably, this range for  $V_{\text{excess}}$  indicates the KI data resolve, but do not over-resolve, the  $K$ -excess, and this result is robust even incorporating the large uncertainty in  $r$ . For instance, if the dominant  $K$ -excess came from a warm inner-edge of the circumbinary disk (nominally at a barycentric distance of

**Table 2**  
Characteristic Angular Scales for Simple Morphological Models of DQ Tau  $K$ -band Excess

Model	Characteristic Scale (mas)	Note
Gaussian	1.1–1.4	Gaussian FWHM
Ring	1.3–1.7	Ring Diameter
Uniform Disk	1.9–2.4	UD Diameter

**Note.** Assuming  $V_{\text{excess}} = 0.85\text{--}0.77$ .

$\approx 0.4$  AU; Artymowicz & Lubow 1994; Pichardo et al. 2005), the apparent inner-edge diameter would be  $\sim 5.7$  mas. The  $V$  of such a ring morphology would be  $\sim 0.1\text{--}0.2$ . Apparently the  $K$ -excess is dominated by emission from a region significantly more compact than the dynamically allowed inner edge of the circumbinary disk. Our visibility measurement supports the M1997 and C2001 conclusion that there is warm material in the vicinity of the DQ Tau binary, and emission from that material dominates the system’s  $K$ -excess.

If we neglect  $K$ -emission from the circumbinary disk entirely (the equilibrium temperature of material at 0.4 AU is on the order of 475 K), we can estimate the angular scale of emission from the warm material. Table 2 summarizes a small set of simple assumed emission morphologies for the  $K$ -excess: Gaussian profile, thin ring, and uniform disk. Under these assumptions the characteristic apparent size required to match the  $V_{\text{excess}}$  estimate is given. Of these three models we expect the Gaussian profile most closely matches the warm material emission profile; we note that this assumption results in a size scale (1.1–1.4 mas; 0.15–0.2 AU at 140 pc) that closely matched the apparent binary separation at apastron ( $\sim 1.5$  mas). Incoherent scattered light from the circumbinary disk (proposed for CTTS by Pinte et al. 2008) would make this warm material characteristic size estimate smaller.

## 5. DISCUSSION

We have modeled our DQ Tau observations based on orbital parameters from M1997 and system SED. Unsurprisingly, the significant  $K$ -excess must be included in the  $V^2$  modeling. Remarkably these data indicate the excess must come from a region smaller than the circumbinary disk. Further, our data suggest that this excess is distributed on the physical scale of the binary orbit ( $\sim 0.1\text{--}0.2$  AU) rather than being either much smaller (e.g., circumstellar disks) or much larger (i.e., the circumbinary disk) than the stellar separation.

Our data and modeling support the M1997 and C2001 inference that DQ Tau has significant warm material in the inner orbit region (in addition to the substantial circumbinary disk). Binary dynamics, accretion, and wind/outflow processes work to dissipate this inner material over a few binary orbital periods. The static visibility offset that adequately models our KI data

over many DQ Tau orbital periods suggests the system is in quasi-equilibrium with material inflow replenishing dissipated material in the binary region.

It is important to note that our present data on and modeling of this remarkable system are relatively crude. In particular the  $\sim 5$  mas KI fringe spacing only partially resolves the  $\sim 1$  mas DQ Tau binary orbit. Clearly limited spatial information leads to limitations in our DQ Tau modeling, and some care in interpreting our conclusions is warranted. Our construct that the  $K$ -excess morphology is axisymmetric seems the most suspect; it runs counter to existing modeling of accreting binary systems (e.g. Artymowicz & Lubow 1996), and photometric/accretion brightening near periastron (M1997). However, nothing more sophisticated is justified by our data—in particular the KI data from our last epoch (2007 October 28) test the axisymmetric modeling assumption to the practical limits of KI capabilities (in broadband data). But there should be an asymmetric component to the near-IR flux at some contrast level and spatial scale in the DQ Tau system. Going forward it is important to probe the extent of any axisymmetry in the near-IR excess at a greater diversity of spatial scales and wavelengths to understand the distribution and flow of material in DQ Tau and similar systems.

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